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AGILE observation of terrestrial gamma-ray flashes

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Summary. — Terrestrial Gamma-ray Flashes (TGFs) are very short (up to a few milliseconds) energetic bursts of photons and electrons originating from severe thunderstorms mainly in the equatorial and tropical regions. Although several production models have been proposed so far, TGFs still remain a mystery since there is not wide consensus yet on their acceleration mechanism, production sites, maximal energy and fluence. AGILE, operating since mid 2007, is detecting hundreds of TGFs with the Mini-Calorimeter (MCAL) instrument. Thanks to the MCAL energy range extended up to 100 MeV and its flexible trigger logic on sub-millisecond time scales, AGILE is adding a wealth of observations which pose severe constrains on production models. In this paper we will describe the main characteristics of the AGILE TGF sample, focusing on the recent results concerning the first localization of TGFs at gamma-ray energies by means of the AGILE silicon tracker.

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1. – Introduction

Terrestrial Gamma-Ray Flashes (TGFs) are very short (lasting up to a few milliseconds) bursts of high-energy photons above 100 keV, first detected by the BATSE instrument on board the Compton Observatory [1], and later extensively observed by the RHESSI satellite [2, 3]. TGFs have been associated with strong thunderstorms mostly concentrated in the Earth's equatorial and tropical regions, at a typical altitude of 15–20 km [4]. TGFs are widely believed to be produced by bremsstrahlung in the atmospheric layers by a population of runaway electrons accelerated to relativistic energies by strong electric fields inside or above thunderclouds. The secondaries generated during the acceleration process can be accelerated as well driving an avalanche multiplication [5], commonly referred to as Relativistic Runaway Electron Avalanche (RREA), possibly further enhanced by means of a relativistic feedback mechanism [6, 7]. Although being widely accepted as the underlying physical process in TGF production, the RREA mechanism alone is not sufficient to explain the rich phenomenology of TGFs, especially the observed fluence, and there is no consensus yet on the underlying physical conditions, production sites, radiation efficiencies and maximal energies.

Recently, the AGILE satellite added a wealth of spectral and geographical data on TGFs and established itself as a major player in TGF observation, together with the RHESSI [2] and *Fermi*-GBM detectors [8]. AGILE [9] is a mission of the Italian Space Agency (ASI) dedicated to astrophysics in the gamma-ray energy range 30 MeV–30 GeV, with a monitor in the X-ray band 18 keV–60 keV [10], operating since April 2007 in a low inclination (2.5°) Low-Earth Orbit at 540 km altitude. The AGILE Gamma-Ray Imaging Detector (GRID) is a pair-tracking telescope based on a tungsten-silicon tracker [11], sensitive in the 30 MeV–30 GeV energy range. The imaging principle is based on the reconstruction of the tracks left in the silicon detection planes by the electron-positron pairs produced by the primary photon converting mainly in the tracker tungsten planes. A Mini-Calorimeter (MCAL) [12], based on CsI(Tl) scintillating bars for the detection of gamma-rays in the range 300 keV–100 MeV, and a plastic anti-coincidence detector [13] complete the high-energy instrument. MCAL can work also as an independent gamma-ray transient detector with a dedicated trigger logic acting on several time scales spanning four orders of magnitude between 290 μs and 8 seconds [14, 15].

The main AGILE discoveries in TGF science during two and a half years of observations are the following:

1) the TGF spectrum extends at least up to 40 MeV [16] (well above the previous 20 MeV limit set by RHESSI [2]);

2) the high energy tail of the TGF spectrum is harder than expected and cannot be easily explained by previous theoretical models [17];

3) TGF can be localized from space using high-energy photons detected by the AGILE silicon tracker [18].

In this paper we will present the general characteristics of the AGILE TGF sample and focus on the recent results of the first TGF localization by means of the AGILE silicon tracker.

2. – AGILE observation of TGFs

Thanks to its flexible trigger logic on sub-millisecond time scales [14], MCAL proved to be a very efficient instrument for TGF detection. The average MCAL detection rate is ~ 10 TGFs/month, with the current severe selection criteria based on hardness ratio and fluence [16]. For a trigger to be classified as a valid TGF candidate, at least 10 photons and a hardness ratio $HR \geq 0.5$ are required, where HR is defined as the ratio between the number of counts with energy greater than 1.4 MeV and the number of counts with energy lower than 1.4 MeV.

Figure 1 shows the geographical and local-time distribution of the AGILE TGF sample detected between June, 2008, and January, 2010. There is evidence for events clustering on the African continental region and the south-east Asia. The geographical distribution, strongly peaked over continental areas, matches the distribution of lightnings over the equatorial region, confirming the association of the TGF phenomenon with thunderstorm activity. The local-time distribution, peaked over the mid-afternoon hours, reflect the thunderstorm activity over equatorial areas as well. The geographical and local-time distributions are in good agreement with those of the RHESSI sample, provided the same latitude interval is considered [16, 3], strongly suggesting that the two instruments detect consistent populations.

3. – AGILE localization of TGFs in gamma-rays

In the period between June 2008 and December 2009 the MCAL instrument triggered 119 bursts identified as TGFs according to the selection criteria discussed in [16]. For each of these bursts, the GRID dataset was searched for quasi-simultaneous gamma-ray events within a 200 ms time-window centered at the TGF start time T_0, defined as the time of the first MCAL-photon associated with the TGF. A peak in the time-of-arrival distribution is evident for the 2 ms time bin immediately following T_0. This peak includes 13 events, and the probability for it to be a statistical fluctuation (13 events or higher) is $6.5 \cdot 10^{-10}$ if we assume that GRID events are not correlated to TGFs and are distributed

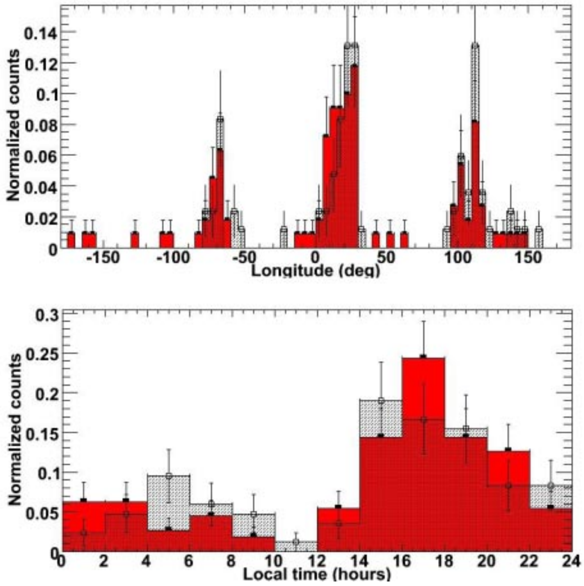

Fig. 1. – (Colour on-line) Geographical (top panel) and local time (bottom panel) distribution of AGILE TGFs (red histogram) detected between June, 2008, and January, 2010. The grey histogram shows the same distributions for the RHESSI TGFs [3] detected within $\pm 2.5°$ latitude.

according to the Poisson law with the measured average rate of 5.1 counts/s. All these GRID events take place during the TGF emission time interval estimated from MCAL data only. The relatively low fraction (10%) of TGFs having at least one high-energy photon detected by the GRID is due to a combination of factors including the high energy threshold for GRID detection (~ 20 MeV), the lower GRID effective area than MCAL, and the further decrease of the detection efficiency for high off-axis angle photons.

Among these 13 GRID events, 9 of them have incoming direction compatible with the Earth, an average energy of 60 MeV, and can be directly associated to the TGF (see [18] for a detailed description of the data analysis process). All TGFs in the selected sample have one associated GRID event except the remarkable case of TGF 12809-19, for which two closely spaced GRID events were detected. Both of these photons, separated by about 250 μs, come from directions compatible within errors with the same production site on Earth, further strengthening the evidence for their terrestrial origin and correlation with the TGF.

The incoming directions of the 9 selected events appear to be clustered close to the subsatellite point, with an average (maximum) ϕ angle (the angle between the photon direction and the satellite nadir) of $25.4°$ ($35.1°$) and distance to the subsatellite point of 260 km (390 km).

Figure 2 shows the scatterplot of the GRID events projection with respect to the AGILE footprint (the point at the Earth's surface on the straight line joining the satellite and the Earth's centre), and the distribution of the occurrence density *vs.* distance from footprint (each bin has been divided by the subtended area in km^2). The GRID photon directions are obtained by the standard analysis pipeline for photons within the AGILE field of view, and by a custom version of the same software for photons outside the field

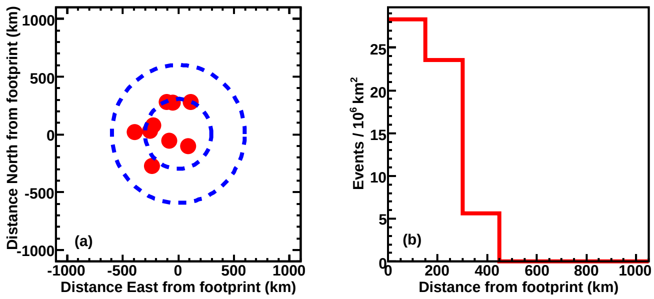

Fig. 2. – (a) Scatterplot of the GRID events projection with respect to the AGILE footprint. The dashed circles are 300 and 600 km in radius. The full AGILE visibility region has a 2600 km radius. (b) Occurrence density *vs.* distance from footprint (each bin has been divided by the subtended area in km^2).

of view. The photon directions are then back-projected from the satellite position, obtained by GPS data, to the Earth's surface, parameterized as the World Geodetic System WGS-84 ellipsoid, in order to obtain the production site location. All 9 events are contained within a 1.14 sr solid angle, a factor 3.4 smaller than the solid angle subtended by the Earth at the satellite altitude of 540 km, which corresponds to a maximum visibility projected distance radius of $\sim$ 2600 km from the satellite footprint. If the GRID events originate directly from the TGF production site, these results are consistent with a distance to footprint less than $\sim$ 300 km estimated for RHESSI TGFs using sferics data [19-22].

4. – Conclusions

AGILE is succesfully observing TGFs since June 2008 and is currently one of the only three operating space instruments capable of detecting TGFs. The AGILE payload is very well suited for TGF science. Its main strength points can be summarized as follows:

- AGILE-MCAL effective area peaks in the MeV range, the range where most of the TGF energy is radiated;
- the MCAL energy range is extended up to 100 MeV, allowing to probe the high energy tail of the TGF spectrum;
- the trigger logic on time scales as short as 1ms and 290 μs, well matching the TGF typical time scale, makes the AGILE sample not biased toward the brightest/longest events;
- the MCAL design strategy, spatial segmentation in several independent detection units, makes the instrument less sensitive to dead-time and pile-up effects than monolithic detectors of equivalent volume;
- event data with 1 μs timing accuracy are available for triggered events: time binning is limited by counting statistics only;
- absolute timing accuracy better than 100 μs allows precise timing for correlation with on-ground observation of sferic waves associated to lightnings;

– the AGILE-GRID trigger logic is sufficiently flexible to collect also high-energy photons coming from the Earth;

– the AGILE orbit with 2.5° inclination is optimal for mapping the equatorial region, where most of the TGFs take place, with exposure much larger than other missions.

Thanks to these capabilities, several important results on TGF science based on AGILE observations have already been published [16-18], especially concerning the yet poorly understood TGF high-energy component. Moreover, our detection of TGFs with an imaging gamma-ray detector provides the first accurate localization (within a few degrees) of TGFs from space, and shows that the TGF high-energy emission is detected by satellites in Low Earth Orbits (LEO) from a relatively small region within 300–400 km from the satellite footprint. Future investigations will determine whether the apparently narrow cone of detected gamma-rays is due to beamed emission intrinsic to the TGF source or caused by a selection effect favored by absorption and Compton scattering in the atmosphere.

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